M.R.P. 930
S.C. 1/103
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Some further determinations made by the M.R.F. of the speed correction coefficients of aircraft thermometers

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AIR MINISTRY
METEOROLOGICAL RESEARCH COMMITTEE

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Some further determinations made by the M.R.F. of the speed correction coefficients of aircraft thermometers

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Summary

An account is given of recent determinations by the M.R.F. of speed correction coefficients of flat plate and conical head aircraft thermometers on Ashton and Canberra aircraft.

Both series of flights, up to 35,000 ft. in the Ashton aircraft and 40,000 ft. in the Canberra aircraft, showed no consistent variation with height of these coefficients, although there was a large scatter in the determined values.

A thermometer mounted by the manufacturers on the leading edge of the Canberra aircraft's port wing, and indicating on a meter in the navigator's position, showed a large increase with height of its speed correction coefficient.

It is concluded that future work on the improvement of thermometer design should await further investigation of the causes of the random variation of the determined values of speed correction coefficients. Pending such investigation the flat plate or the conical head thermometer is considered to be as good an indicator of free air temperature as any other type of aircraft thermometer now available.

1. Introduction

In M.R.P. 527(1), which gave an account of flight determinations by the M.R.F. of the speed correction coefficients of the M.O. flat plate resistance thermometer and the R.A.E. pitot head thermometer, it was concluded that these coefficients decrease with increasing height. In M.R.P. 822(2) an account is given of attempts to verify this and the results obtained did not support the previous findings. It was thought that with regard to heights and airspeeds outside the limits of the aircraft then available (viz. a Hastings) it might well be that the speed correction coefficients varied with height in some regular manner but that further experimental work by the M.R.F. should await the availability of aircraft with a wide speed range at great heights. Meanwhile a series of flights(3) made in a Meteor VII aircraft at R.A.E. between sea level and 36,000 ft. produced fresh evidence of speed correction coefficients decreasing with height.

This problem came to the fore once again in the latter half of 1953 in connexion with the instrumentation of a Canberra aircraft which had just been allocated to the M.R.F. There happened to be an Ashton aircraft available at the same time, and some calibration trials were also carried out with thermometers fitted to this aircraft, mainly in order to provide a comparison with the data obtained on the Canberra.

/2.

2. Ashton flights

(i) Instrumentation

The thermometers used on the Ashton were

(a) a flat plate thermometer,

(b) a flat plate thermometer with two trip wires arranged ahead of the element to ensure that it was always in their turbulent wake,

(c) a conical head thermometer, made at the M.R.F. and shown in Fig.4.

The flat plate thermometers had elements with resistances of about 120 ohms and the resistance of the element of the conical head thermometer was about 160 ohms.

All three thermometers were mounted underneath and about midway along the starboard wing of the Ashton aircraft. Each thermometer was connected to a ratiometer and these together with altitude and airspeed indicators were mounted in an auto-observer panel. The panel was automatically photographed every 10 sec. by an F.24 camera.

(ii) Flight procedure

The speed runs were made in a manner similar to that described under the heading "Flight Procedure" in part I of M.R.P.822(2) but with increased height and airspeed ranges. The flying on this work was through the courtesy of Mechanical Engineering Dept., R.A.E. who allowed the observations to be made during their own investigations.

In all there were six flights in which it was possible to make speed runs. The flights were made at heights ranging from 5,000 ft. to 35,000 ft. with indicated airspeeds between 108 and 280 kt. The maximum number of levels at which pairs of speed runs were made on any flight was three and the maximum number of pairs of speed runs made at any level on any flight was also three. Each pair of speed runs consisted of one run at high speed and the other at low speed. In the calculations of the speed correction coefficient full position errors (including calibration compressibility errors (see Appendix B)) were allowed for.

3. Canberra flights

(i) Instrumentation

The thermometers used on the Canberra were

(a) a flat plate thermometer,

(b) a conical head thermometer,

(c) a thermometer installed on the port wing by the manufacturers.

(a) and (b) were the same thermometers as those used on the Ashton aircraft flights. (a) and (c) were used on all twelve flights but (b) was used on the first eight flights only.

Thermometers (a) and (b) were mounted under the nose of the Canberra aircraft, the flat plate to starboard and the conical head to port. The thermometer installed by the aircraft manufacturers is of the resistance type, the element of which is contained in a small cylinder, about 3 cm. long and 1 cm. diameter, which juts out from the leading edge of the port wing.

/(ii)

(ii) Flight procedure

On each flight readings of the flat plate and conical head thermometers were obtained from M.O. balanced bridges while the readings of thermometer (c) above were displayed on a ratiometer dial in the navigator's position. The two bridge readings and the height as displayed by a pressure altimeter were made by one member of the crew and the readings of airspeed, height as displayed by a radar altimeter and thermometer (c) were made by another member of the crew.

The lapse rate at the level of the speed runs was obtained by taking readings during one-minute runs 1,000 ft. below and 1,000 ft. above the operating level. By arranging these supplementary runs to be at the same speed the lapse rate was found directly from the difference of the indicated temperatures.

The speed runs themselves consisted of five-minute runs on two reciprocal bearings, one at high speed (about 340 kt. I.A.S. at heights up to 20,000 ft. and 230 kt. I.A.S. at 40,000 ft.) and one at low speed (about 140 kt. I.A.S. at all heights), readings being taken every 30 sec. Runs were made in clear air and at least 2,000 ft. above or below any cloud. Although it was the original intention to confine the speed runs to the levels 5,000, 20,000 and 40,000 ft. the presence of cloud made it necessary to fly at levels other than 5,000 ft. (usually 10,000 ft.) on some occasions and at 25,000 ft. instead of 20,000 ft. on one occasion. The runs were flown at constant radar altimeter height (as far as possible) and the values of the speed correction coefficients were obtained by three methods. The first method allowed for full pressure error correction to both height and airspeed. The second method made no allowance for position (pressure) error but allowed for calibration compressibility error to the airspeed. In the third method an attempt was made to use the readings of a radar altimeter to allow for static pressure errors to the airspeed, calibration compressibility errors having already been allowed for. The method does not provide any correction for static pressure errors in the altimeter readings. It has been shown however in Ref. 2 that the former normally give rise to errors in the speed corrections which are much greater than those produced by the latter. Provided that the radar altimeter gives correct readings this method should give a good indication of the accuracy of the pressure errors used in method 1.

4. Results

The results of the Ashton aircraft flights are given in Table 1 and those of the Canberra aircraft flights in Table 2.

Because of the small number of observations possible at levels up to 20,000 ft. with the Ashton aircraft, the results for 5,000, 10,000, 15,000 and 20,000 ft. were combined and those for 30,000 and 35,000 ft. were also combined.

(a) Flat plate thermometer

There is no evidence of any systematic variation of the speed correction coefficient with height and the mean values for all levels were 1.83 and 1.76 for the Ashton and Canberra aircraft respectively.

(b) Conical head thermometer

There is no evidence of any systematic variation of the speed correction coefficient with height and the mean values for all levels were 2.01 and 1.92 for the Ashton and Canberra aircraft respectively. These values are greater than those for the flat plate thermometer and Student's "t" tests carried out to determine the probabilities for each type of aircraft that these higher values of α could have arisen by chance, gave probabilities of only 4% for the Ashton aircraft and 0.05% for the Canberra aircraft. Combination of these two probabilities by a χ^2 test indicates a combined chance probability of only 0.5%.

/(c)

(c) Navigator's thermometer

There is no evidence of any systematic variation of the speed correction coefficient with height between 5,000 and 20,000 ft. where the mean value is 2.30 but the mean value at 40,000 ft., 2.94, is significantly larger. A "Fisher-Behrens" test carried out to compare these two mean values gave a level of significance of less than 0.1%. This difference between the means results in a large value for the standard deviation for all levels, given in Table 2 as .35.

The value of 2.94 is greater than that which would be realised by full kinetic heating ($\alpha \simeq 2.38$). It is thought that the indicated airspeed values can not be applied directly to the position where this thermometer is mounted and it is doubtful whether the usual law of $\Delta T = \alpha (V/100)^2$ can be correctly applied in this case.

(d) Flat plate thermometer with trip wires

This thermometer, which was used only on the Ashton aircraft, had greatly reduced values of the speed correction coefficient compared with the ordinary flat plate thermometer. Otherwise no effects as regards variation with height through the use of these trip wires were detected.

(e) To test the significance of the larger values of the standard deviations of the speed correction coefficients at 40,000 ft. compared with lower levels, "Variance Ratio" tests were carried out for the flat plate, conical head and navigator's thermometers. These gave significance levels of about 6%, $2\frac{1}{2}$% and 1% respectively. Clearly, some additional effect, most marked in the case of the navigator's thermometer, is in evidence at 40,000 ft.

5. Discussion

It appears from the results obtained that within the speed range of these experiments there is no consistent variation with height of the speed correction coefficients of the flat plate and conical head thermometers. This is in agreement with the findings of M.R.P. 822(2) but not with those of M.R.P. 527(1) or Ref. 3. The results also show a very large scatter.

The immediate purpose of this work was to provide values of the speed correction coefficients of the existing thermometers used by the Meteorological Research Flight and to estimate the accuracy with which temperature measurements can at present be made at high levels. From these results it appears that at levels up to 20,000 ft. the probable error of all the thermometers examined is less than 0.5°F. at speeds up to 200 kt. but increases with speed to about 2°F. at 450 kt. At 40,000 ft. the probable errors are somewhat larger being about 0.7°F. at speeds up to 200 kt. and about 3.5°F. at 450 kt.

In considering these errors, it must be remembered that the accuracy of all work on aircraft thermometry depends on the accuracy of the altimeter and air-speed indicator.

In all three methods of calculation the observed values of α showed considerable random variation which increased at high levels and it is apparent that the reason for it lies in the original observational data rather than in the method of calculation. Provided that calibration compressibility errors are initially allowed for, different methods of allowing for static pressure errors to the airspeed do not appreciably affect the result except at 40,000 ft. At this level values of α calculated by method 3 were significantly less than the corresponding values calculated by method 1. This suggests that at levels up to 20,000 ft. the static pressure errors used in method 1 are correct but that at 40,000 ft. they may be too small. This is contrary to evidence given in M.R.P. 926 which maintained that at 40,000 ft. the pressure errors used were correct. The true explanation of the discrepancy is not known but the consequence is to reduce the mean values of α . In the case of the flat plate thermometer α is reduced from 1.76 to 1.74 which has the effect of increasing the corrected value of the temperature by an amount which increases with speed from a negligible amount at 100 kt. to about 0.5°F. at 500 kt.

/It

It must be stressed however that the main reason for the scatter in the calculated values of α is that the original temperature data have a large scatter and it is not at all evident why this should be so. It was not found, however, that the deviations of individual values of speed correction coefficients from the mean values were associated with the angle at which the speed runs were flown across the thermal gradient. It might be that the scatter is in some measure due to the effect of atmospheric inhomogeneities.

Another possible cause of the scatter is concerned with differences in flow over the thermometer surfaces at different heights and airspeeds. In this respect, it is known that the practice of making speed runs at different levels using the same range of indicated airspeed masks any effects due to changes in Reynold's number. Such changes probably contribute to the variations in α from one level to another but do not provide an explanation of the scatter found at a particular level. The inference is that the scatter at any level and from one level to another are due to some other factor.

It is thought that further work on the causes and elimination of the scatter of the original observations is necessary before further progress can be made in the design of aircraft thermometers. Meanwhile it is considered that either the flat plate thermometer or the conical head thermometer is as good an indicator of free air temperature as any other type of aircraft thermometer now available.

Acknowledgements

Acknowledgements are due to Mr. R. J. Murgatroyd at whose suggestion the work was carried out and to whom the suggested method of using the radar altimeter is due. The author is also indebted to the Mechanical Engineering Dept., R.A.E. for the use of the Ashton aircraft.

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APPENDIX A

Methods of calculating the speed correction coefficients

Equation (3) of M.R.P. 822 gives as a good approximation the result

$$\alpha = \frac{(T_H - T_L)P}{\frac{1\cdot95}{100^2}\left\{V_H^2(T_L+459) - V_L^2(T_H+459)\right\}} \qquad \text{-----(1)}$$

where T = indicated temperatures in degrees Fahrenheit,
V = equivalent airspeed (see Appendix B) in kt.,
P = pressure in mb.

Suffixes "H" and "L" refer to the values at the fast and slow speeds and it is assumed that both runs were made at the same pressure level. This assumption is rarely true however and more accurately

$$\alpha = \frac{T_H - (T_L + dT)}{\frac{1\cdot95}{100^2}\left\{\frac{V_H^2}{P_H}(T_L+459) - \frac{V_L^2}{P_L}(T_H+459)\right\}} \qquad \text{-----(2)}$$

where P_H and P_L are the pressures corresponding to indicated altimeter heights for the fast and slow speed runs respectively and where dT is the amount by which the true air temperature at the level at which the fast run was made exceeds that at the level at which the slow run was made.

Equation (2) was used in the first two methods of calculation, the only difference being that in the first method the indicated pressure heights and airspeeds were corrected for full pressure errors (including calibration compressibility errors) and in the second method airspeeds were corrected for calibration compressibility errors only. The latter correction is always necessary in this work.

The correction for position (pressure) error at the static source is necessary whenever the lapse rate departs considerably from the saturated adiabatic value (Ref. 2). Hence it will usually be small in the troposphere except in inversions and large in the stratosphere. The relative accuracies of the above two methods are related to the deviation of the actual lapse rate from the saturated adiabatic value.

In the third method of calculation it is assumed that the static pressure is in error by an amount dP. This can be regarded as giving rise to an error dZ in true pressure height where

$$dZ = -\frac{dP}{g\rho} \qquad \text{-----(3)}$$

where ρ is the density of the ambient air and g is the gravitational constant.

Let P and V' be the true pressure and true airspeed respectively at the level of flight. Then, from Bernouilli's equation for steady flow of an inviscid fluid (viz. $\int \frac{dP}{\rho} + \frac{V'^2}{2} = \text{constant}$) it follows that a pressure error dP can also be regarded as giving rise to an error dV' in true airspeed where

$$dP = -\rho V' dV' \qquad \text{-----(4)}$$

It follows that if dP is <0, dZ and dV' must be >0. In other words, due to a negative static pressure error within the static tube, both airspeed indicator and altimeter read high.

/Furthermore

Furthermore, the pressure height of the aircraft will differ from the true height of the aircraft by an amount that depends on the difference between the actual atmosphere and the standard I.C.A.N. atmosphere.

Combining equations (3) and (4)

$$dZ = V' dV'/g \qquad \text{.....(5)}$$

For the fast and slow speed runs

$$dZ_H = V_H' dV_H'/g \quad \text{and} \quad dZ_L = V_L' dV_L'/g$$

so that $$dZ_H - dZ_L = \frac{1}{g}(V_H' dV_H' - V_L' dV_L') \qquad \text{.....(6)}$$

Fig.1 illustrates the notation and the circumstances in which dP is a negative static pressure error so that dZ_H and dZ_L are errors in indicated height due to the error dP. dZ_H' and dZ_L' are the differences between I.C.A.N. pressure heights and the true heights, and for simplicity of illustration are shown in Fig.1 as arising from an atmosphere that is colder than the standard I.C.A.N. atmosphere.

From Fig.1 it will be seen that

$dZ = Z'' - Z'$ and $dZ' = Z' - Z$ for both high and low speed runs. Hence

$$(dZ_H - dZ_L) = (Z_H'' - Z_L'') - (Z_H - Z_L) - (dZ_H' - dZ_L')$$

Now, $Z_H - Z_L$ is the difference between the radar altimeter readings which are assumed to be correct and $Z_H'' - Z_L''$ is the difference between the indicated pressure heights for the high and low speed runs. $(dZ_H' - dZ_L')$ is the difference between a small height interval (equal to the difference between the mean height at which the high and low speed runs were flown) and the response to it of a pressure altimeter. Assuming no instrument lag, this difference will be small compared with $(Z_H'' - Z_L'') - (Z_H - Z_L)$ and may be ignored. Hence

$$(Z_H'' - Z_L'') - (Z_H - Z_L) = \frac{1}{g}(V_H' dV_H' - V_L' dV_L') \qquad \text{.....(7)}$$

It is shown (4) that the relation between true and indicated airspeeds is given by

$$V' = V\left[1{\cdot}95(T'+459)/P\right]^{1/2}$$

where T' is the true air temperature in $^{\circ}F$, P the true air pressure in mb. and where the true airspeed V' and indicated airspeed V are in knots. At any particular level of flight therefore

$$dV' = dV\left[1{\cdot}95(T'+459)/P\right]^{1/2} \qquad \text{.....(8)}$$

If allowance is made for the static pressure errors to the airspeed, equation (2) becomes

$$\alpha = \frac{T_H - (T_L + dT)}{\frac{1{\cdot}95}{100^2}\left\{\frac{(V_H - dV_H)^2}{P_H}(T_L+459) - \frac{(V_L - dV_L)^2}{P_L}(T_H+459)\right\}}$$

where V_H and V_L are the airspeeds corrected for calibration compressibility only and dV_H and dV_L are the static pressure errors to the airspeed.

The new denominator is less than the denominator of (2) by

$$2\frac{(1{\cdot}95)}{100^2}\left\{\frac{V_H\, dV_H}{P_H}(T_L+459) - \frac{V_L\, dV_L}{P_L}(T_H+459)\right\}$$

neglecting the terms containing $(dV_H)^2$ and $(dV_L)^2$.

/Using

Using equation (8) this becomes $\frac{2}{100^2}\left(V_H' dV_H' - V_L' dV_L'\right)$ where the approximations

$$\frac{T_H+459}{T_L'+459} = \frac{T_L+459}{T_H'+459} = 1$$ are made.

Finally, using equation (7) this expression becomes $\frac{29}{100^2}\left\{(Z_H''-Z_L'')-(Z_H-Z_L)\right\}$ and the modified equation for the third method of calculating the speed correction coefficient becomes

$$\alpha = \frac{T_H - (T_L + dT)}{\frac{1{\cdot}95}{100^2}\left\{\frac{V_H^2(T_L+459)}{P_H} - \frac{V_L^2(T_H+459)}{P_L}\right\} - \frac{2}{100^2}\left\{(Z_H''-Z_L'')-(Z_H-Z_L)\right\}}$$

APPENDIX B

Note on the corrections to be applied to indicated airspeed readings

An airspeed indicator and altimeter do not in general correctly indicate the "free stream" (i.e. away from the pressure field surrounding the aircraft) pressures from which the speed and pressure altitude must be deduced. The calibrations of these instruments are chosen so that the derivation of the free stream pressures from the indicated pressures is a simple process. In the case of the airspeed indicator the scale equation is

$$P_D = \tfrac{1}{2}\rho_0 V_R^2 \left(1 + \tfrac{1}{4}\frac{V_R^2}{a_0^2}\right)$$

where P_D is the dynamic pressure, ρ_0 and a_0 are the density of air and the speed of sound under standard sea level conditions and V_R is the actual reading of the airspeed indicator.

If the free stream conditions were applied to the pitot static system the corresponding equation would be

$$P_d = \tfrac{1}{2}\rho_0 V_r^2 \left(1 + \tfrac{1}{4}\frac{V_r^2}{a_0^2}\right)$$

where P_d is the dynamic pressure in the free stream and V_r is the airspeed indicator reading corresponding to P_d.

Under standard sea level conditions and in the absence of compressible flow, V_r would be the same as the true airspeed V. Compressibility is however always present to some extent and its effect under standard sea level conditions is to introduce a difference between V_r and the true airspeed. This error is small at low speeds but increases with speed and is due to compressibility not being allowed for in the original calibration of the instrument. It is called the Calibration Compressibility error.

When the airspeed indicator is used under conditions of free stream air density ρ (i.e. different from ρ_0) and in the absence of compressibility the true airspeed V is equivalent to an airspeed V_i (which is what the instrument would read) called the "Equivalent Airspeed". V_i is related to V by the equation

$$V_i = V(\rho/\rho_0)^{1/2}$$

Again allowing for compressibility, the indicated airspeed V_r differs from the equivalent airspeed V_i due to the calibration compressibility error.

Conditions of air density and true airspeed (and hence equivalent airspeed) in the free stream differ from those at the static source due to position error so that the actual indicated airspeed V_R depends on the equivalent airspeed at the static source.

It follows that to obtain true airspeed V from indicated airspeed V_R it is necessary first of all to find the equivalent airspeed in the free stream, V_i. This involves knowing the position error and calibration compressibility error and they are obtained by means of the "aneroid method". The values near the surface are found by comparing the aircraft heights as read on the altimeters with those obtained from ground photography as the aircraft flew low over the runway at various speeds. These results are then extrapolated to altitude by the method of Ref. 5. The errors for both the Ashton and Canberra aircraft were obtained in this way and are plotted as combined errors in Figs. 2 and 3.

Table 1

Ashton Aircraft Results

Type of thermometer	Height (ft.)	Number of measurements	Mean α	Standard deviation	Greatest α	Smallest α
Flat plate	5,000, 10,000, 15,000, 20,000 (combined)	6	1.82	.22	2.12	1.58
	30,000, 35,000 (combined)	8	1.83	.18	1.96	1.42
	all levels	14	1.83	.20	2.12	1.42
Flat plate with trip wires	5,000, 10,000, 15,000, 20,000 (combined)	7	0.99	.37	1.51	0.67
	30,000, 35,000 (combined)	8	1.07	.31	1.43	0.41
	all levels	15	1.03	.31	1.53	0.41
Conical head	5,000, 10,000, 15,000, 20,000 (combined)	9	1.94	.17	2.26	1.66
	30,000, 35,000 (combined)	8	2.08	.43	2.84	1.48
	all levels	17	2.01	.32	2.84	1.48

Table 2

Canberra Aircraft Results (all values)

Type of thermometer		Height (ft.)	No. of measurements	Mean α (Method 1)	Mean α (Method 2)	Mean α (Method 3)	Standard deviation	Greatest α Method 1	Smallest α
Flat plate	*	5,000	5	1.78	1.80	1.78	.12	1.92	1.60
	*	10,000	6	1.80	1.81	1.80	.12	1.93	1.59
	*	20,000	9	1.67	1.69	1.68	.11	1.76	1.42
		40,000	11	1.81	1.83	1.73	.20	2.25	1.58
		all levels	31	1.76	1.78	1.74	.15	2.25	1.42
Navigator's	*	5,000	5	2.28	2.29	2.27	.14	2.37	2.15
thermometer	*	10,000	6	2.28	2.31	2.28	.15	2.53	2.04
	*	20,000	9	2.34	2.36	2.35	.11	2.50	2.13
		40,000	11	2.94	2.99	2.84	.23	3.43	2.65
		all levels	31	2.53	2.56	2.50	.35	3.43	2.04
Conical head	*	5,000	4	2.01	2.02	1.99	.08	2.08	1.94
	*	10,000	3	1.91	1.93	1.92	.15	2.03	1.74
	*	20,000	6	1.93	1.94	1.93	.16	2.03	1.61
		40,000	7	1.87	1.89	1.81	.25	2.31	1.54
		all levels	20	1.92	1.94	1.90	.17	2.31	1.54

* includes one value at 3,000 ft. at 5,000 ft. level, one value at each of 8,000 ft. and 9,000 ft. at the 10,000 ft. level and one value at 25,000 ft. at the 20,000 ft. level.

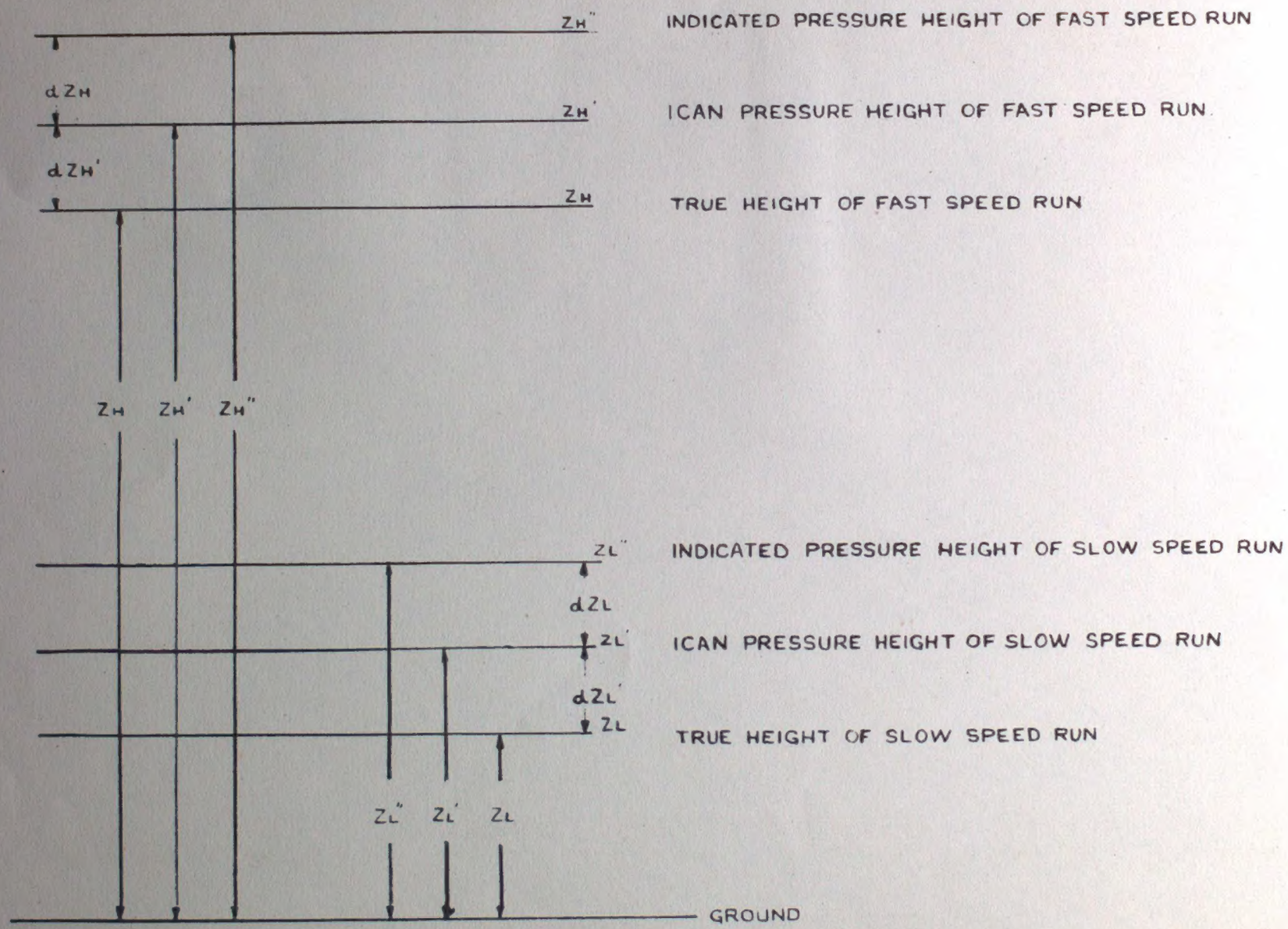
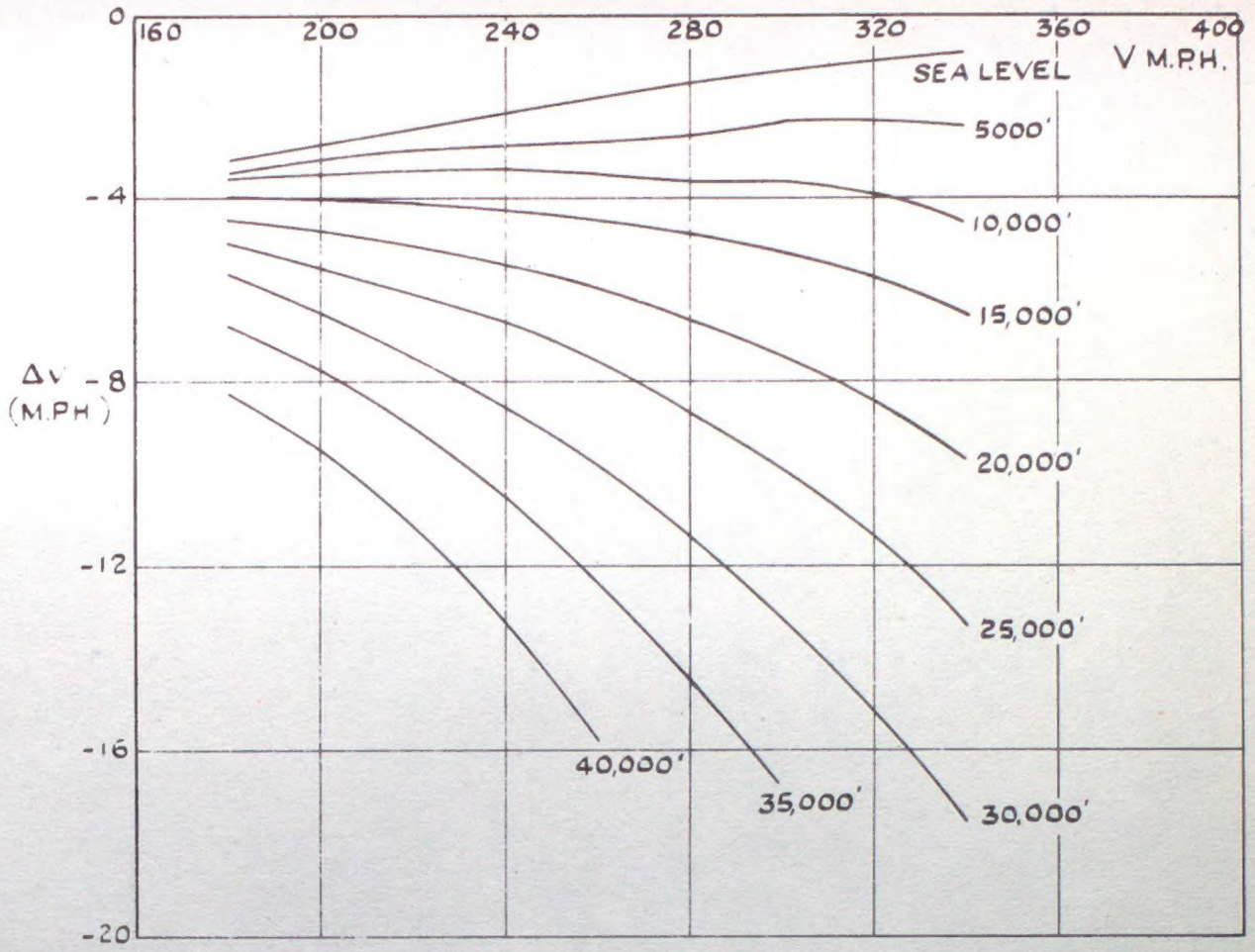


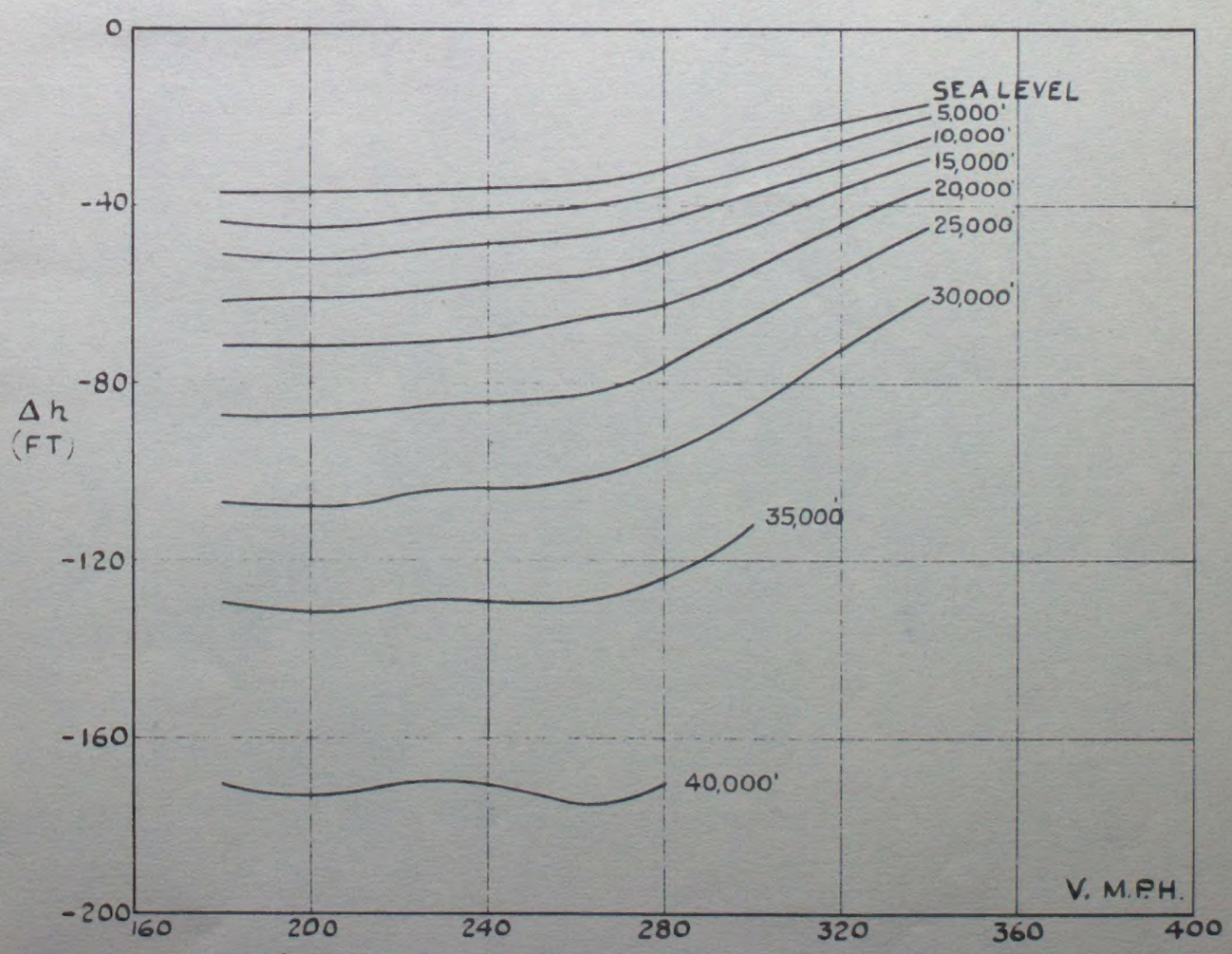
FIG. 1. DIAGRAM OF NOTATION USED IN THE THIRD METHOD FOR CALCULATION OF SPEED CORRECTION COEFFICIENTS.

M.R.P. 930 FIG. 1.

FIG.2.a & b.



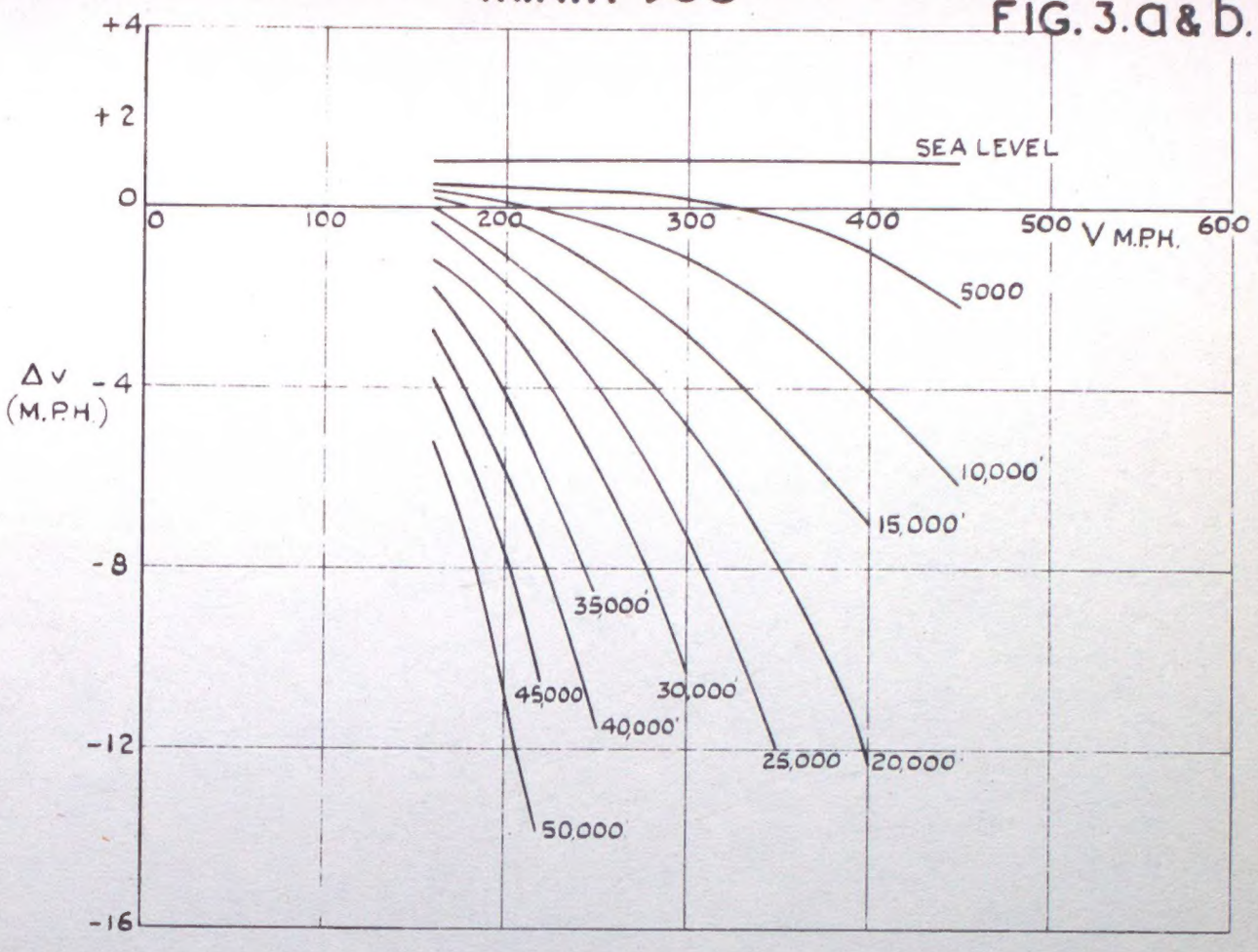
a. INDICATED AIRSPEED.



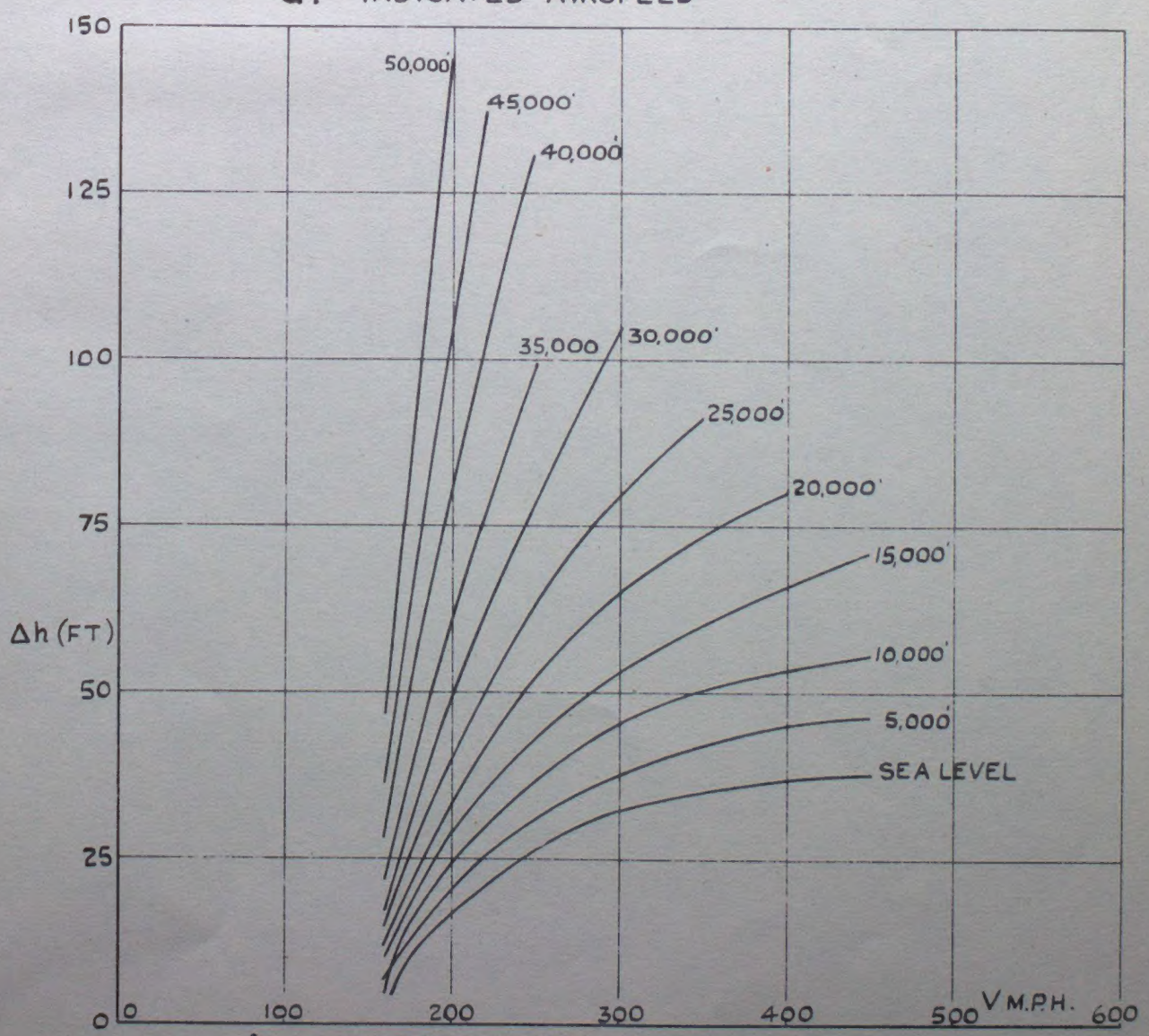
b. INDICATED PRESSURE HEIGHT.

FIG.2. a & b. COMPLETE ASHTON CORRECTIONS.

FIG. 3.a & b.



a. INDICATED AIRSPEED



b. INDICATED PRESSURE HEIGHT

FIG 3.a & b. COMPLETE CANBERRA CORRECTIONS.

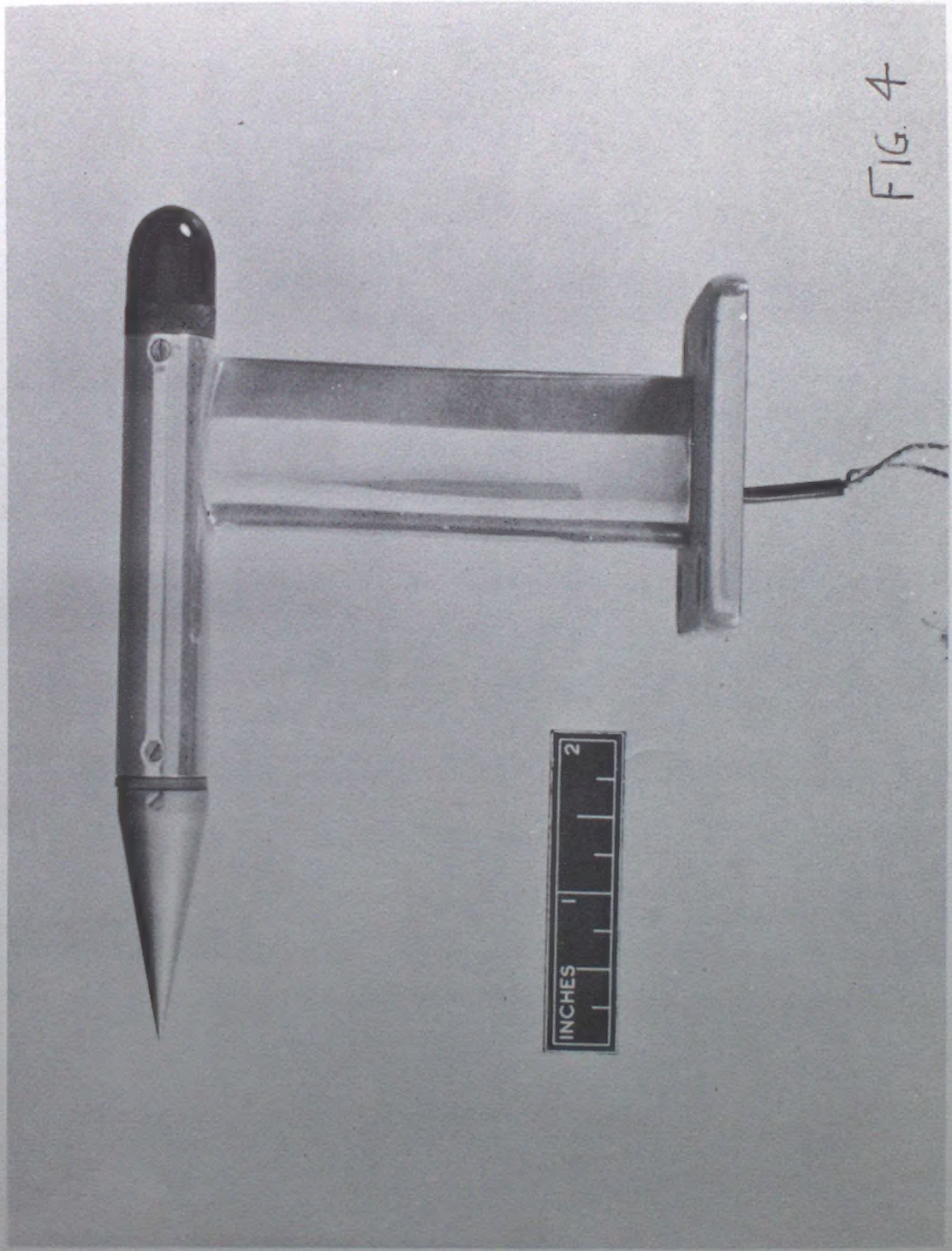


FIG. 4